

Solar Array Automation Limitations

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ABSTRACT

Significant progress in the automation of the spacecraft electrical power systems has been made within the past few years. This is especially important with the development of the space station and the increasing demand on the electrical power systems for future satellites. The key element of the spacecraft power system, the solar arrays which supply the power, will have to grow to supply many tens of kilowatts of power within the next twenty years. This growth will be accompanied by the problems associated with large distributed power systems. This paper addresses the growth of the arrays, the on-array management problems and potential solutions to array degradation or failure. This paper will be primarily limited to the discussion of multikilowatt arrays for unmanned spacecraft with comments of the implications of array degradation for manned spacecraft.

Additionally, the need for an expert at the ground station becomes obvious when the problem presented by the EPS does not lend itself to straightforward solutions. Within the past few years, ground based experts have become expert systems. They act more rapidly and reliably than their human counterparts, however they have to wait for the communication window between the satellite and the ground station. Additionally, they are based upon past measured performance with the identification of specific anomalies and correction or compensation procedures. This type of information is available for the EPS but is not generally available for solar arrays. Solar arrays themselves are almost devoid of instrumentation and are basically, fixed configuration, electrical power generating systems. In order for them to survive on an unmanned spacecraft, they must have the same advantages as those provided for manned spacecraft. The man-in-the-loop must be replaced fully by a sensing, assessing, problem solving entity. In short, the array itself must take on human characteristics.

1. Introduction

The electrical power system (EPS) requirements for large unmanned satellites are considerably different from those of manned satellites. The large size of manned spacecraft, such as the space station, requires considerable electrical power to ensure a long, useful mission. Maintenance of the health of the system is provided by the combination of expert systems and human judgment. The envelop of possibilities for maintaining the electrical power system using this combination of man and machine are almost unlimited. Determination of the abrupt degradation of the array can be as simple as visual assessment, or as complex as a computer analysis of the electrical system performance correlated with orbit location and maneuvering constraints. All of the options invariably include the human in the loop.

At the present time, for the unmanned spacecraft, human prognosis and intervention in the case of an EPS anomaly, is limited by the information provided about the array and the physical limitations of communicating with the spacecraft from a number of ground stations.

2. Solar Array Considerations

The solar arrays under consideration are planar, oriented arrays as opposed to spacecraft body mounted arrays or solar concentrator arrays. A 10 kilowatt array of silicon solar cells will require about 61 square meters of area. This can be broken down into several smaller arrays, typically four arrays of slightly over 15 square meters. Conventional arrays on the order of 10 to 15 kilowatts have already been built and tested in the support of manned spacecraft. The problems encountered were dealt with in a reactive fashion rather than a proactive fashion. The short, limited lifetime of these arrays has not been a major problem in the past. With the requirement to last 10 years, unattended, arrays of this size require on-array instrumentation, processing and communications with the main EPS computer.

The new breed of solar cells for planar arrays have reached the 20% efficiency plateau. This reduces the 10 kilowatt array size from 61 square meters to 42 square meters, a reduction of over 30 percent. In the 21st century, spacecraft requirements can be expected to grow to 50 or 100 kilowatts. In the worst case scenario, using ultralight silicon solar cells 100 kilowatts would occupy 420 square meters. How can the problem of maintaining adequate power from such a large array for over a decade be accomplished

without a human performing extra vehicular activity (EVA)? The solution lies in the design of a self monitoring array with the capability to reconfigure itself.

3. Design Philosophy

Selection of the array voltage is a critical parameter that must be considered before all other considerations. The selection of the voltage is orbit dependent and beyond the scope of this paper. The selection of 160 volts direct current (VDC) however, has been chosen as a practical voltage that is applicable to different spacecraft orbits. Configuring the array into blocks of solar cells to produce 160 VDC can most easily be accomplished by putting 185 gallium arsenide (GaAs) solar cells in series, and paralleling at least five series strings. A block of 925 2 cm X 2 cm solar cells then provides 100 watts of power, with a total of 1000 blocks required for the 100 kilowatt array.

Using these numbers, it is now possible to discuss some of the requirements and alternatives available to ensure ten years of uninterrupted power from the array. An obvious improvement can be made if one poorly performing series string of 185 GaAs solar cells could be dropped off-line and replaced by a properly functioning cell string. This would require 5,000 switching transistors, one for each of the cell strings. The 5000 switching transistors would replace the diode isolators used for each cell string. Each transistor would be required to switch 20 watts. Each transistor could be designed so that it could communicate through the B+ lines. It could be used as a current sensor which would allow it to provide this information to a local microprocessor responsible for comparing current from all the switches. The new string would automatically go on-line through either a command from a local microprocessor tracking the number of cell strings on-line, or automatically as a result of the transistor providing the low current information.

On-array sensing (Figure 1) must be accomplished if array integrity is to be maintained. Voltage sensing can be for the entire array and therefore is rather straightforward. Current sensing should make it possible to identify each series string. Another method to accomplish this task would be to measure the current going through a string by turning a string off then back on. The value of current could be compared to a stored standard. Current (I) and

voltage (V), however, are not the only parameters of interest. The cell string temperature is important, however the penalty for embedding large numbers of temperature sensors in the array to sense the temperature of each cell string would result in at least 5000 sensors with the accompanying communication and conversion requirements. A minimum of one sensor for each segment of the array is necessary. Temperature sensor data from one block can be compared with temperature sensor data from neighboring blocks and a built in reference standard. This allows trends and out of tolerance temperatures to be identified. Predictive solutions can be used if enough historical information can be stored.

Other sensors will also be necessary. For a large array, it is important that accelerometers and vibration pickups be used to provide information describing the mechanical state of the array. Collisions with space debris, orbital corrections, and mechanical failures have to be detected and identified if compensation or correction is to be meaningful. A critical issue that requires clarification is the issue of correction versus compensation. An intelligent array is primarily oriented toward the correction of problems, with compensation as a secondary solution. To correct array problems, the array must be electrically reconfigurable and must have other attributes that make it worth while to extend the lifetime of the array. Annealing gallium arsenide solar cells on the array is one method for correcting a major array problem. Annealing, raising the temperature of the array until solar cell radiation damage has been appreciably reduced, can be accomplished a number of ways. It is conceivable, for example, to pass electrical current through a string of solar cells in the forward direction until the heat generated is adequate to generate annealing. For a large array, it is possible to use several active solar cell strings to forward bias another cell string until it has recuperated 85 to 90 percent of its Beginning-of Life (BOL) power. This cell string can in turn be used to anneal other cell strings.

4. Smart Sensors

The problem of sensors for a large array creates a completely new concept for the array design. It is totally impractical to develop a sensor that requires a power supply to operate, a separate amplifier and power conditioner, and miles of shielded cable. The alternatives are quite

obvious. Smart sensors must be developed. A smart sensor, for this case, is described as an integral sensor/microprocessor package that operates off the solar array B+ voltage and uses the electrical wiring for both communicating with the array processors and providing sensor information. With this concept, embedded sensors make sense and weight penalties become negligible. On-array communication between the main on-array microprocessor and microprocessors distributed across the array will require a handshake or token protocol to ensure that each microprocessor is operating properly. If the main computer on-board the spacecraft fails to query the on-array main microprocessor, this microprocessor would query the main computer to determine its health. Failure of the main computer to respond would then allow the main on-array microprocessor to fully control the array with reporting still being continued to the main computer as a matter of routine. The communication between the smart sensors and the on-array computer would require that the smart sensor have a priority token. When there is any change in the status-quo for the sensor, it sends out its priority token with the sensor information. As the information is received the priority arrives with it to allow the microprocessor to select the most important information. The details of operation of such a system can be worked out by several methods, but will not be discussed in this paper.

5. Sensor Information

The basic rule for the use of sensor generated information is to minimize it. Smart sensors will not provide output data unless there is a status change. This step will minimize the inputs to the control microprocessors. The second step is to use as few sensors in combination as possible to generate an action. Use of accelerometer data and vibration pickup can be algorithmically combined to indicate a mechanical collision on a specific array segment. This information combined with the current sensor information for that segment provides high confidence that a specific number of cell strings are affected and that switching in of spare cell strings should be done. After array compensation has been completed, further analysis of the damage can be accomplished using other available sensors. The temporal aspects of the problem thus become amenable to simple solutions. In most cases, solutions can be accomplished rather slowly, that

is, in a matter of seconds or minutes. Microprocessor speeds therefore need not be exceptionally fast, however they must be insensitive to the radiation and electromagnetic environment of space.

6. Design Philosophy

Before serious consideration can be given to the specific design of on-array hardware, rules must be formulated for both the array and the autonomous array management system. Rules for the EPS have already been formulated for manned spacecraft systems. This establishes the basis for the interaction between the EPS within the spacecraft and the autonomous array management system, even though these rules must be modified for the unmanned spacecraft case. A simple list is provided to indicate the genesis of these rules.

- a. Reliability is the most important criteria.
- b. Fail safe design required. The array should never degrade worse than it would without and autonomous system to manage it.
- c. Minimize components count.
- d. Minimize weight.
- e. Design for long term performance.
- f. Minimize on-array data taking, processing and storage.
- g. Sense and verify critical data.
- h. Establish a temporal basis for data analysis.
- i. Transmit only new information from sensors.
- j. Verify sensor integrity on a continual basis if practical.

These rules are provided as a basis from which to develop a complete design philosophy for the autonomous array operation and establish the basis for rules in a rule based on-array expert system. The expert system will most likely not be of a straightforward forward or backward chaining design.

7. Expert System

With the progress that has been made in the aerospace industry in the development of expert systems for the control and monitoring of the spacecraft EPS, much of the work for a fully autonomous EPS and an autonomous solar array has been completed. The present systems require a man in the loop, however there are several direct

techniques for replacing the man. The concept of power management, in many cases provides the crewmember with data after the fact. With the appropriate action already taken, this process is fully autonomous. This is generally applied to load sharing, shedding and prioritization, a major portion of the main EPS power management activity. The on-array expert system has to work closely with the spacecraft EPS computer. This interface and its requirements represent a large complex problem requiring a lengthy detailed analysis. The goal is to establish the on-array main microprocessor as an independent entity requiring minimum memory and microprocessor code. Although ADA and FORTH are proposed as candidates for the on-array language, the selection on the final language must be based upon the self maintenance of the array and its reliable function. Since there will be no maintenance of the system once it is in space all other criteria for the selection and use of a language fall by the wayside.

8. Summary

This paper is intended to provide insight into the design problems associated with a large fully autonomous array. Most of the major problems have been discussed in a fashion that will allow the reader to approach the problem with his own artificial intelligence tools. Most importantly, the paper is designed to provide the basis for the development of a sound philosophy for the development of an autonomous array. The development of an autonomous array should be considered only after alternatives such as Extra Vehicular Activity (EVA) have been considered. If it is feasible to accomplish on-site repairs in space, the design of the array will have to be modular and easy to repair. Safety of the person doing the EVA then becomes a concern because of the space environment and the array voltages. Regardless, whether a fully autonomous array becomes necessary or not, the hardware and software should be considered for development to ensure the operation of large unattended arrays both for spacecraft and for surfaces of other planets or moons. Solar array systems must be smarter if they are to survive.

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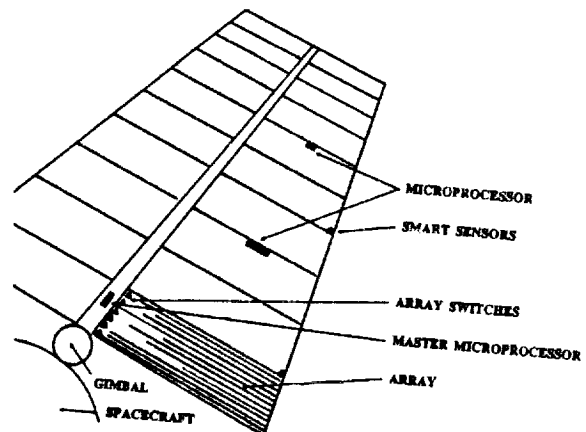


FIGURE 1